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DIGITAL RECORDING USING HOLOGRAM ARRAYS: development of the transducers for an experimental 100 Mbit/s recorder

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Summary

Three special transducers for use with an experimental holographic recorder have been partly developed. They are a hologram page-composer with 50 ports, a solid-state digital light-deflector and a photodetector array for intercepting 100 light-beams.

The page-composer is based on an electro-optic ceramic material, PLZT, in the form of a large slice placed between two matched arrays of lenses. This device produces 50 collimated digit-beams each of which can be modulated independently by external electronic switches. Generally, performance was good but some problems remain in the fabrication process and in the need to improve the dissipation of the heat generated in the PLZT.

The digital light-deflector comprises several stages of electro-optic crystals coupled with passive Wollaston prisms. A high transmission efficiency demands care to minimise internal surface reflections. The first large aperture stage, operating at the highest switching rate (10^6 transitions/sec) was difficult to design, and the deflector performance was limited by the lack of suitable high-voltage transistors for the electronic switches.

The development of a suitable photodetector array for operation at low light-levels was less of a problem. The design consists of a bundle of 100 monofilament light-guides attached to silicon photodiodes and followed by low-noise amplifiers.

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1. Introduction

Earlier Research Reports in this series on digital holographic recording describe the basic principles,[1] discuss various methods of modulating and deflecting laser beams,[2] and present the optical design of a proposed system for recording digital television signals.[3] The proposed method, which makes use of laser sources and high resolution photographic film, is based on the concept of sequentially recording small (micro) holograms each containing 50 bits of information. The holograms ($\simeq$ 50 x 50 μm) are recorded in rows across the film which moves continuously from reel-to-reel.

Briefly, in the recording process, a two-dimensional array of fifty (parallel) digit-beams is derived from a laser source. These are passed through a 50-port modulator or page-composer, whereby the 'state' of each digit-beam is set (e.g. 'on' or 'off') in accordance with the binary states of the particular block of signal data to be recorded. The digit-beams emerging from the page-composer, at any one instant, correspond to one 'page' of data, and a Fourier-transform hologram of the page is recorded on the film. A new page is then composed and, by means of a light-deflector, the hologram of the new page is recorded at the next position in the row, and so on.

On replay, a scanning laser-beam (focused to about the same size as a hologram) is used to interrogate the processed film record. As the laser spot passes over a hologram, an image of the original page appears on the far side of the film. An array of photodetectors is placed so as to intercept the reconstructed digit-beam and detect their presence (or absence). For every digit-beam in the 'on' state during recording, a (twin) pair of digit-beams is obtained on reconstruction[1] and one or both of the beams can be detected, although they only represent one bit of information.

A recording and replay apparatus was designed for operation at a transfer rate of 100 Mbit/s, which is about the rate required for high-quality digital television recording, and an experimental version has been partly constructed to test the feasibility of the system.

Some of the principal components required, such as the laser sources, can be well-engineered commercially-available units. However, there are three special transducers which need considerable technological development in order to meet the system objectives. These key devices are a hologram page-composer with 50 ports, a seven-stage digital light-deflector, and a 100-element photodetector array for the 50 twin digit-beams. Details of the development and construction of experimental versions of these transducers, which accounted for a large part of the project effort, are given in this Report.

2. Hologram page-composer

2.1. Objectives

The basic requirements for the page-composer were discussed in some detail in a previous report.[2] Briefly, the performance objectives can be summarised as follows:

(a) To produce fifty separate digit-beams in a prescribed geometrical array.[3]

(b) To be able to modulate (switch) each digit-beam between 'on' and 'off' states independently with the minimum of optical and electrical interbeam crosstalk.

(c) To be capable of switching the 'state' of each digit-beam within 100 ns and at average rates up to 10^6 transitions/second, using the minimum drive voltage and power.

(d) To be able to achieve on/off contrast ratios in the recorded hologram greater than 20:1.

(e) To have a high optical efficiency for blue light (λ = 441 nm).

2.2. Construction

The measured characteristics of some formulations of the electro-optic ceramic material, PLZT,* developed by Land *et al* at the Sandia

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*Polycrystalline lead zirconium titanate.

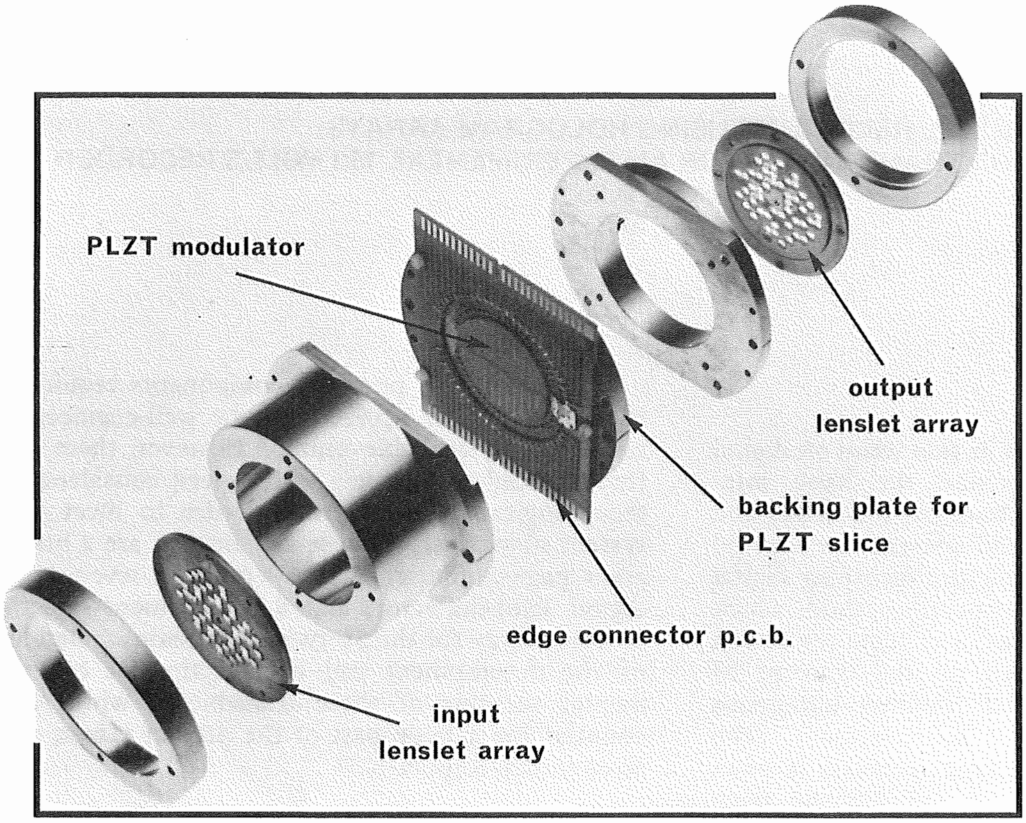

Fig. 1 - Exploded view of the page-composer

Laboratories[4] and the availability of large slices of the material at low cost, made it attractive for constructing page-composers.[5] Moreover, initial experiments showed that PLZT was just capable of handling a 2 Mbit/s data stream[2] providing that the transverse electric field at each digit-beam location was confined to a small material volume. Consequently, it was necessary to use input lenses to focus the incident light on the PLZT modulator slice and then recollimate the transmitted light with a second (output) set of lenses.

2.2.1. Basic arrangement

An experimental page-composer was constructed as shown in Fig. 1, which is an exploded view of a completed unit. It consists of three main components in tandem; an input set of fifty small lenses (lenslets), a PLZT modulator plate assembly and a matching output set of lenslets, When illuminated by an expanded and collimated laser beam, the input lenslet array serves to produce fifty digit-beams, disposed in a pre-determined array (see Reference 3), and to bring each beam to a focus at the surface of the PLZT modulator plate. After transmission through the modulator plate, the digit-beams diverge at first but are recollimated by the output lenslet array. The ray diagram for a single digit-beam is shown in Fig. 2, where it will be noted that the focal

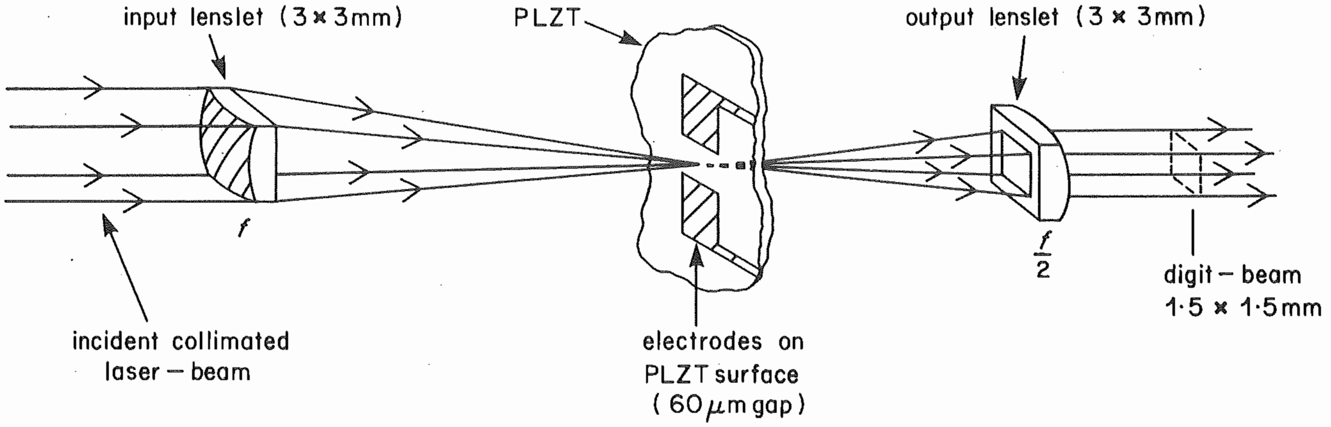

Fig. 2 - Ray diagram for a single digit-beam in the page-composer

length, f, of the input lenslets is twice that of the output lenses in order to obtain the required digit-beam dimensions at the output. The minimum separation of digit-beam axes is 3.1 mm, which is approximately twice the cross-sectional dimension of the output beam.

Ideally, each digit-beam is arranged to pass unobstructed through a small ($\simeq 60$ μm) gap between two conducting electrodes formed on the surface of the PLZT slice (see Fig. 2). A voltage applied to the electrodes creates an electric field in the gap which causes the PLZT to become birefringent in that region. The light transmitted through the birefringent region has its polarisation characteristics altered. If the incident light is plane-polarised at 45° to the electric field, the emerging light will be plane-polarised at 90° to the incident light for a particular applied voltage, V_π, known as the half-wave voltage.* Followed by a polariser, with its axis perpendicular to that of the incident light, the emerging digit-beams will therefore be extinguished except at those locations where the voltage V_π has been applied. Thus, by connecting the electrode gaps to voltage drivers controlled by the incoming digital data, a hologram 'page' of digit-beams can be composed.

A two-part metal housing was designed so that the page-composer could be dismantled and reassembled while still maintaining precise registration between the input and output arrays. Fig. 1 shows that the PLZT modulator is mounted on a separate metal backing plate which is sandwiched between the input and output lenslet housings.

2.2.2. The lenslet arrays

Two experimental versions of the page-composer were made. In the first version, the lenslet arrays were constructed using acrylic moulded lenses which were machined to give a 3mm x 3mm square profile. The lenslets were fixed in the pre-determined array positions by cementing them to a thin glass substrate. However, after assembling and registering the input and output arrays as well as possible, the wavefront distortions of the emerging beams departed so badly from the diffraction-limited ideal that when brought to a common focus again by the holograms lens the spot was unacceptably blurred. Moreover, there was some evidence of a dimensional instability affecting the optical properties of the lenses.

A second version was made using similar methods of assembly but with optically-worked glass lenslets. There were ordinary plano-convex glass lenses which were diced to give a square profile by precision cutting with a diamond saw, as described later.

The input lenslet array was constructed first, placed in the expanded laser-beam input on the recorder and a photograph taken (using a high-resolution plate in the best focal plane) of the actual array of spots obtained. (This master photograph was subsequently used for the photofabrication of the electrode pattern on the PLZT slice as described in Section 2.2.3 below.) The next and most difficult step was to locate and fix the output lenslets in their array so that their optical axes were coincident with the corresponding lenslets in the input set. To achieve this a special alignment jig was set up on an optical bench, using a replica of the optical arrangement on the recorder, and each lenslet was adjusted individually by hand. A diagram of the alignment arrangement is shown in Fig. 3. In this arrangement a collimated input beam was generated on the lower optical bench. This beam was reflected upwards by the mirror M_1, and was incident on the input lenslet array which lay in a horizontal plane. Above the page-composer housing another mirror, M_2 directed the output digit-beams on to the hologram lens, H, on the upper bench. The image formed by H was projected onto a screen by the lens, L, to give a greatly magnified version of the hologram spot. The individual lenslets of the output array rested on a thin glass plate and their approximate position in the array was determined by a metal template containing holes a little larger then the lenslets, to allow for the final adjustments. To make these fine positional adjustments, the end of a small hollow tube, fixed to a metal wand, W, was allowed to rest on top of the lenslet being positioned. The wand was attached at the other end to an X – Y carriage controlled by micrometer lead screws. Thus the lenslet could be pushed around until the image it produced on the screen was seen to coincide with a target marked on the screen. The lenslets were adjusted one at a time and were permanently fixed in position by applying a quick-setting epoxy-resin cement to the underside of each lenslet before adjusting it. Once adjusted, the lenslet was left undisturbed until the resin had begun to harden (approximately 5 minutes).

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* The half-wave voltage is that which produces a phase difference of π radians between the ordinary and extraordinary components of the light propagating through the birefringent cell.

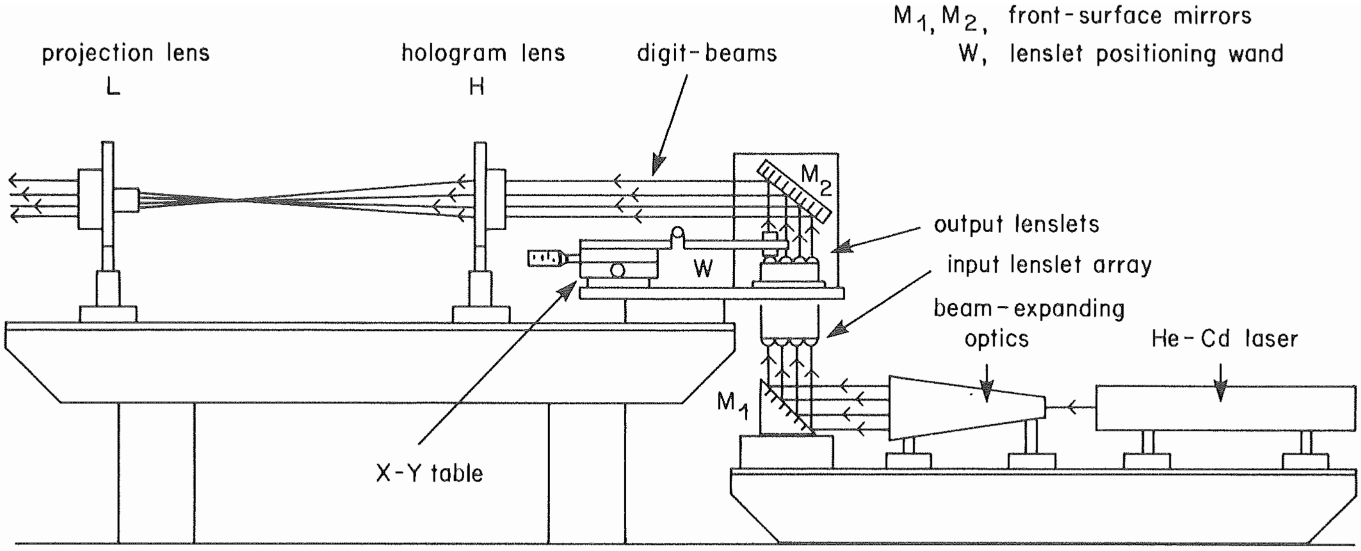

Fig. 3 - Arrangement for aligning the output set of lenslets for the page-composer (target not shown)

Due to small variations in the thicknesses and focal lengths of both the input and output lenslets, it was necessary to try to match the corresponding lenslet pairs by trial-and-error selection. Also, in some locations an axial adjustment of the lenselet was required in addition to the lateral positioning as described above; this was achieved by inserting thin glass spacers.

Special methods were needed for dicing the lenslets prior to assembly. The lenslets were originally 7 or 8 mm in diameter and these were cut into 3mm x 3mm squares in the Department Workshops.* A centering accuracy of ±50 μm was required and this was achieved by waxing a batch of 25 lenslets onto a glass substrate in a 5 x 5 array using metal templates to position them accurately with respect to the cutting axis of the sawing machine. The optical axes of each batch were checked for spacing accuracy using a projection system similar to that shown in Fig. 3. One of the difficulties encountered in this method of dicing arose because of the slight variation in thickness between lenses in the batch. This produced corresponding variations in the thicknesses and therefore the strengths of the wax bonds between the lenslets and the glass substrate. This in turn led to slight lateral shifts during the sawing operation.

2.2.3. Fabrication of the PLZT modulator plate

The modulator plate consists of a 51 mm diameter, optically-polished thin (180 μm) wafer of PLZT ceramic (9% lanthanum-doped) overlaid with 50 pairs of tiny copper electrodes. These are located so that the gaps between each electrode in a pair occur at the points where the light-beams from the input lenslets are focused (see Fig. 2). The electrodes and their associated connecting leads form a metalisation pattern which is plated above the PLZT. In order to keep the inter-channel capacitances low (and hence minimise crosstalk between channels), and to reduce the input capacitance of each port, for minimum drive power, a thick layer of low dielectric-constant ink is applied to the PLZT surface to support the connecting leads. Holes in this layer are provided in the region of the electrode gaps so that the electrodes themselves are directly in contact with the PLZT surface. These features of the construction are shown in Fig. 4, which is a cross-section of the modulator plate in the region of one of the ports near the edge.

The PLZT ceramic wafer is very thin and brittle and requires mechanical support. Also, its surfaces must be anti-reflection coated because of the high refractive index (≃2.8) of the material. A metal-backing plate is provided in close contact with the PLZT to dissipate the heat generated in the electrode gap area at high switching speeds. The edges of the electrodes in the area of the gaps must be free from rough edges to prevent unwanted variations of the electric field. Also, to prevent dust particles spoiling the device during

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* The authors would like to acknowledge the technical assistance given by Mr. F.H. Brown of the Research Department Workshops in the precision cutting and preparation of the lenslets.

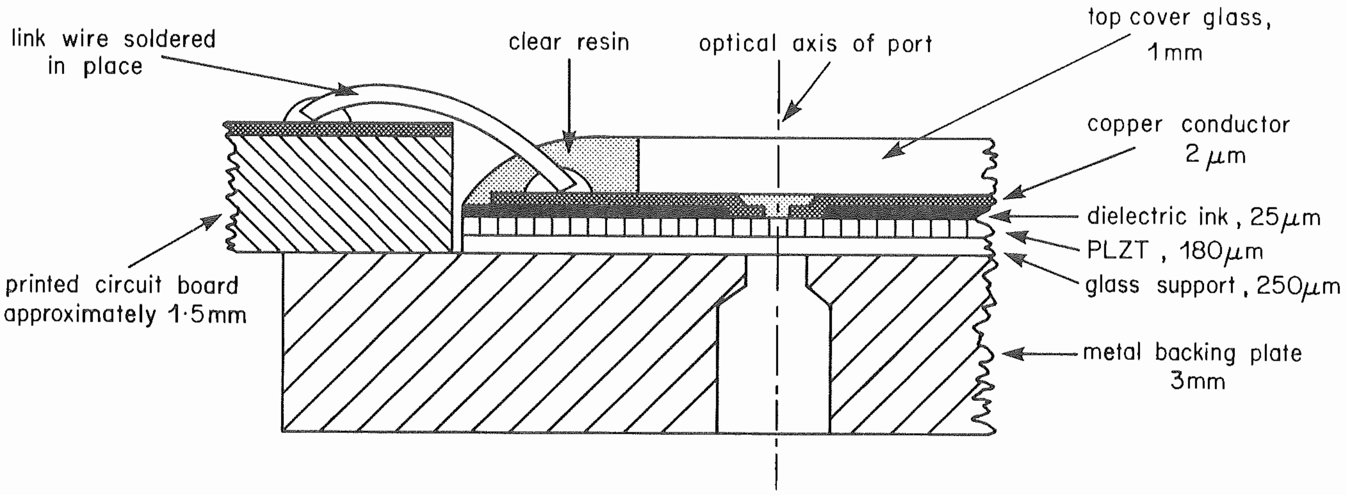


Fig. 4 - Section of the PLZT modulator-plate, including one port

fabrication, the processing environment must be very clean and the stray particle size kept small.

The first step in the construction was to mount the PLZT wafer (anti-reflection-coated underneath) onto a 250 μm thick glass backing for ease of handling and to provide a good thermal contact with the electrode gap areas. The PLZT wafer on its glass backing was then temporarily supported on a glass slide ($\simeq$1 mm thick) for subsequent processing. A silk screen with an appropriate pattern was used to screen print a blue dielectric ink on to the PLZT upper surface. Good adhesion and stability of the ink was achieved by drying for 15 min. at 120°C and further baking for 2 hrs. at 170°C.

After cleaning, a thin coating ($\simeq$100 nm) of aluminium-bronze was vacuum evaporated over the PLZT. The aluminium in the alloy tends to evaporate off first and this adheres well to the PLZT. The copper in the deposited film forms a suitable foundation for the subsequent plating process. The aluminium-bronze surface was coated with a positive-type photo-resist to a thickness of 2.1 μm, dried and exposed to ultra-violet (u.v.) light through a mask bearing the electrode and connecting lead pattern. This mask was produced by similar photo-fabrication techniques based on the spot-location photograph derived earlier. The relevant dimensions of the electrode pairs on this mask were a gap distance of 55 ± 5 μm, and an electrode width of 180 μm.

After development, the exposed areas were electro-plated with copper to a thickness of 2 μm. The remaining resist was removed by re-exposure to u.v. light and further development. The unplated aluminium-bronze was removed by etching in a 5% solution of ferric chloride. The final gap distances obtained were about 60 μm due to slight undercutting in the etching process.

When cleaned, the upper surface of the PLZT was anti-reflection coated, the temporary glass base removed and the PLZT with its thin glass backing cemented directly onto a drilled metal plate to serve as a heatsink – see Fig. 4. The electrode conductor terminations on the modulator plate were connected by fine wires onto a special printed-circuit board, using hot-air soldering techniques. Finally, a cover-glass was cemented over the central area of the modulator for protection. A close-up view of the completed PLZT modulator plate is shown in Fig. 5.

2.3. Driving the modulator

The basic circuits (one required for each port) for operating the page-composer are simple and an early version has been proposed previously.[2] Each switch unit produces 250 V square waves from a data input stream and can supply up to 0.5A per port with transition times of 100 ns. An improved version of the basic circuit is shown in Fig. 6. The output transistors TR2 and TR3 are arranged in common-base configuration to provide a low output capacitance and reasonable voltage gain. From the data input are produced pulses at clock rate which drive TR2 and TR3 via transistors TR6, TR1 and TR7, TR5 respectively. When TR1 is turned 'on' the opposing transistor TR5 is turned 'off' and vice versa. TR1 and TR5 produce large current pulses (up to 0.5 A) when the output changes state (and smaller current pulses at clock rate). These quickly charge and discharge the output capacitance of the circuit and the PLZT load capacitance. In the condition

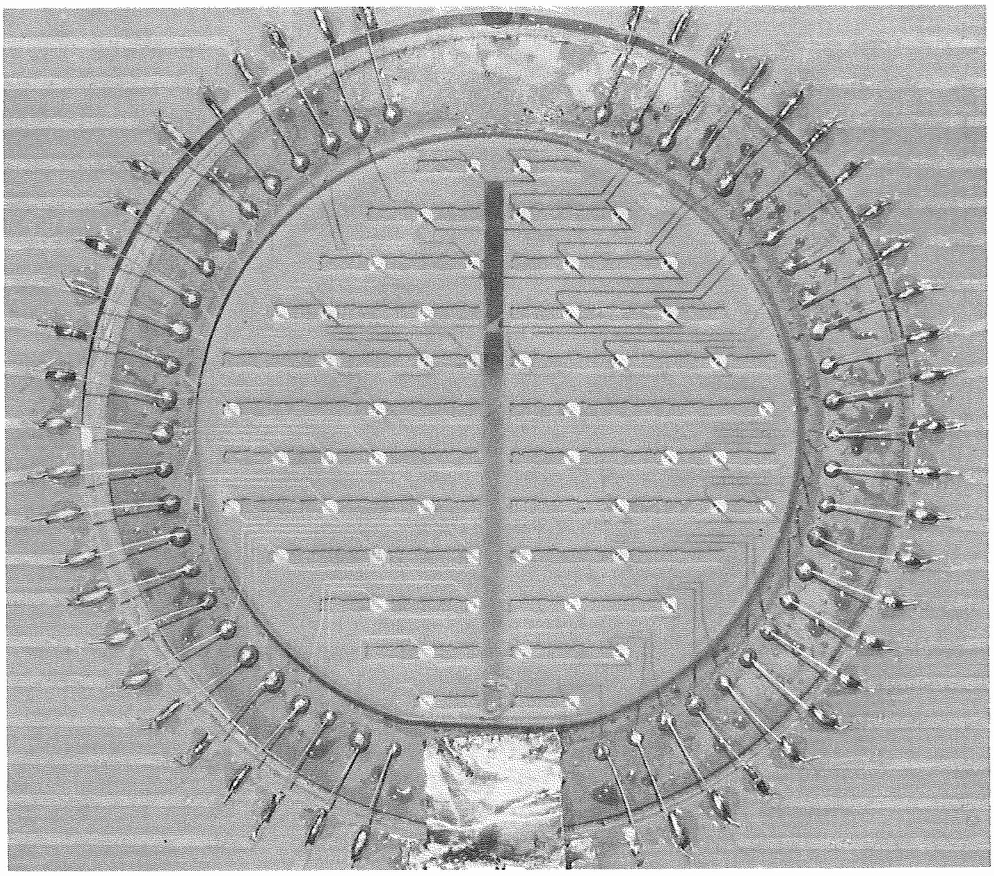


Fig. 5 Modulator-plate conductor pattern.

when TR1 is turned 'on' the current flowing in TR1 causes the output to rise towards the V_{refH} level and be held at a voltage set by V_{refH} and diodes D_2 and D_3. The function of the diodes is to prevent TR2 saturating and to make the circuit response fast. In the condition when TR5 is 'on' the output is pulled down towards V_{refL}.

Crosstalk between channels presented a problem initially and the main reason for introducing the low-dielectric-constant blue ink was to reduce the inter-conductor capacitance and hence reduce the crosstalk. A further improvement was realised by constructing a special low-capacitance cable-form to connect the driver circuits to the page-composer. By these means, the total drive capacitance was reduced from 35 pF to 22 pF.

Fig. 7 is a photograph of the page-composer in-situ on the experimental recorder and shows the low-capacitance 50-lead cable constructed to link the page-composer to the driver switch units (not shown).

PLZT exhibits a photoconductive effect which can result in a loss of contrast between the 'on' and 'off' states of the modulator[2]. To overcome this, the best solution found was to drive the PLZT with a waveform of effectively zero average d.c. content. This was achieved by arranging for the neutral conductor to all ports to be driven with 0 V and 250 V on alternate television fields. To compensate for this, and to maintain the correct switching action of the modulator, the outputs from the 50 data drivers are also inverted on alternate fields.

2.4 Performance

The quality of the recorded holograms is intrinsically dependent on the ability of the page-composer to generate and modulate fifty independent beams efficiently. Various simple tests and measurements were carried out in order to assess the performance of the experimental page-composer.

2.4.1 Transmission losses

Throughout the design and construction, considerable importance was attached to the prevention of wasted light due to reflection and absorption. In the construction of the modulator plate, for example, special anti-reflection coatings were applied to the PLZT slice which otherwise would have a high reflection loss because of its high index of refraction (n = 2.8). PLZT is also slightly

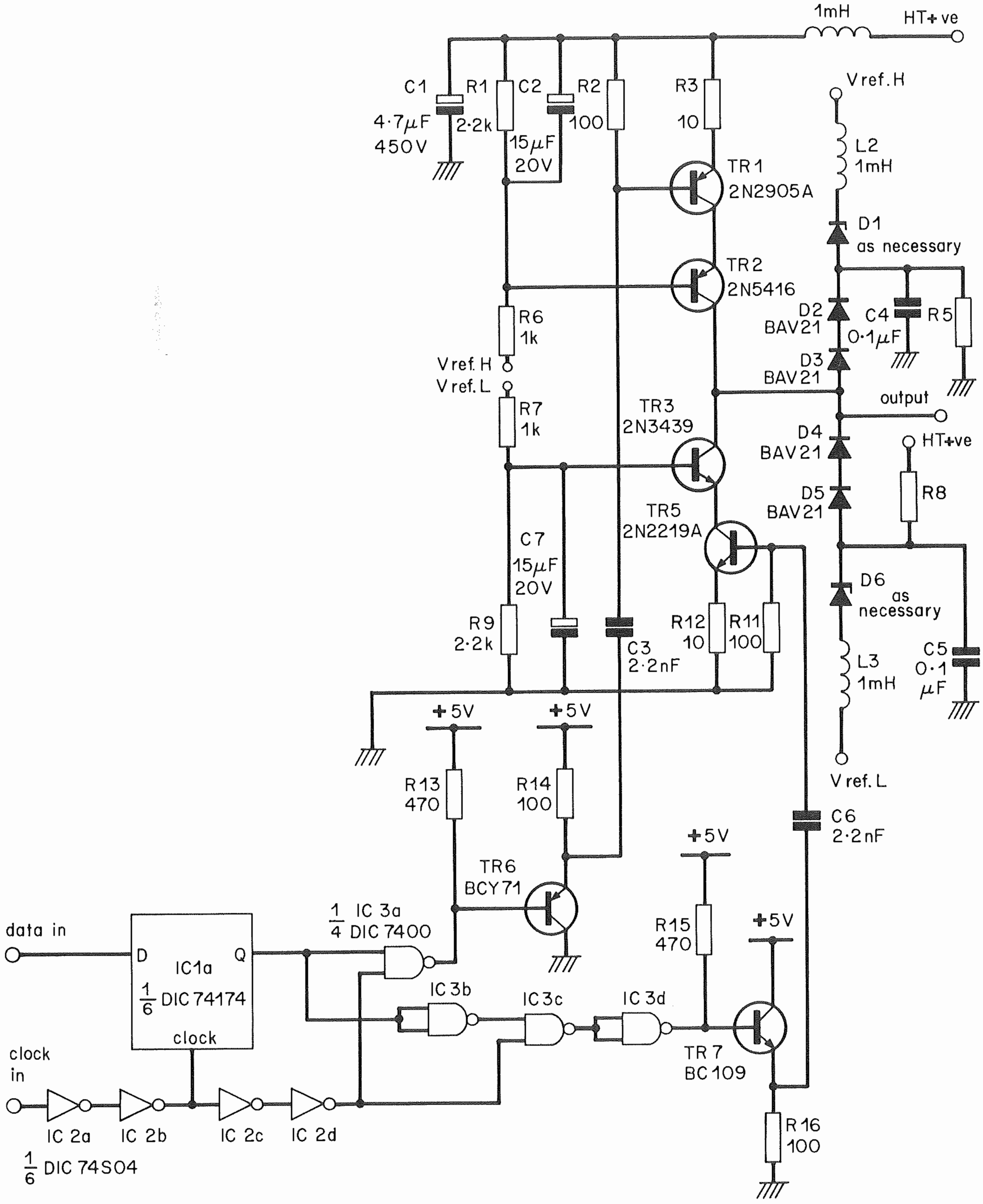


Fig. 6 - Driver circuit for the page-composer.

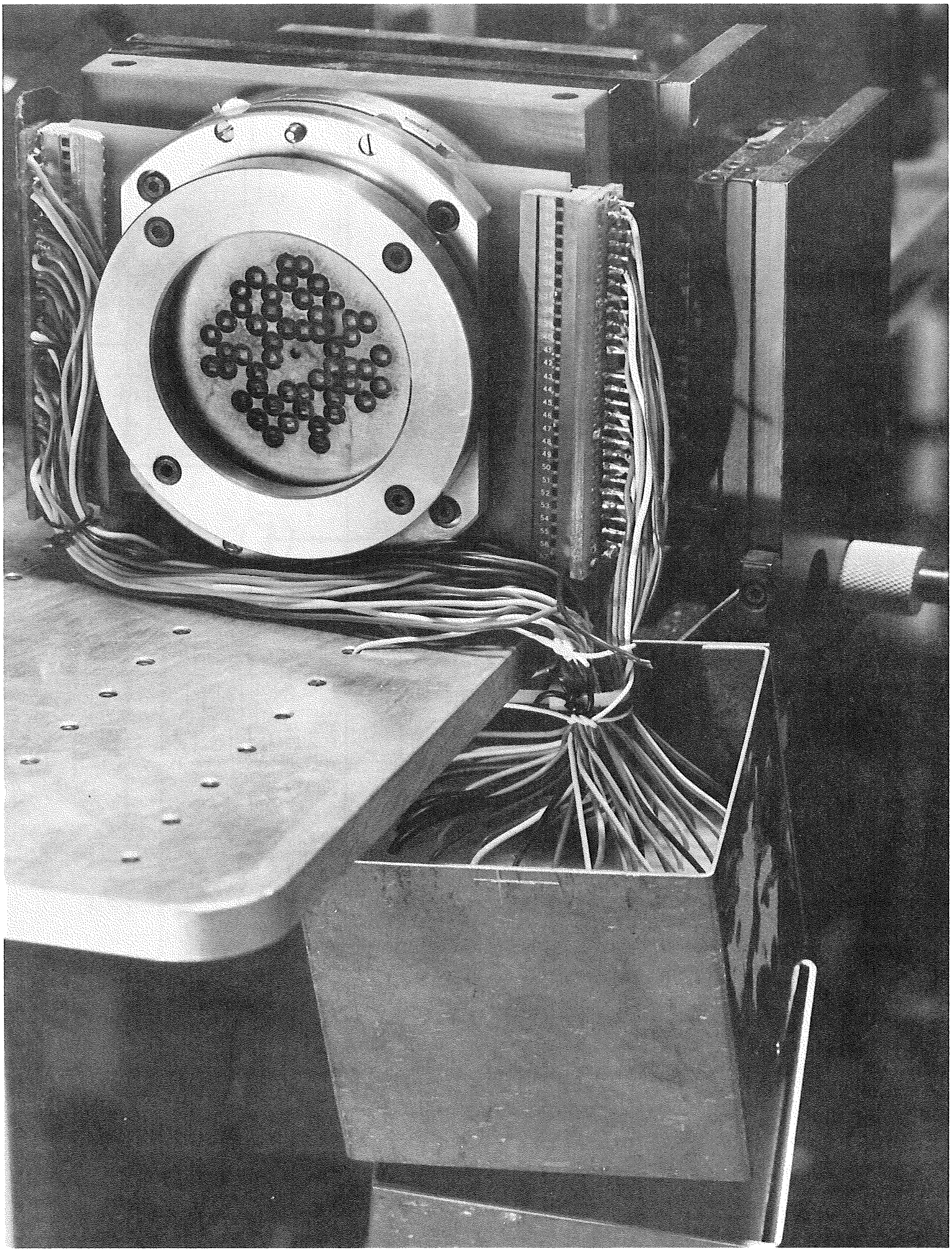


Fig. 7 - The page-composer and driving signal cables in the recorder.

absorptive at the wavelength (λ = 441 nm) used in the recorder and a 180 μm thick slice absorbs about 10% of the incident light. There are also six glass/air interfaces in the page-composer which were "bloomed" with single-layer coatings. The maximum transmission factor for a digit-beam was expected to be approximately 80%. A factor of 70% was measured, showing that there were some additional losses, probably due to imperfect index matching at the glass/cement interfaces and slight absorption in the cement layers.

2.4.2 Wavefront distortion

In an ideal page-composer of the type constructed, the emerging digit-beams would have square cross-sections and their equiphase wavefronts would lie in a single plane. This is an optical condition which could be achieved, for example, by simply placing a thin plate containing an array of rectangular holes in an expanded and collimated laser beam. However, in the actual page-composer the lenslets used were not diffraction-limited even though their numerical apertures were small (0.17). Moreover, defects in the registration, focus and PLZT modulator plate gave rise to slightly aberrated wave-fronts and a lack of collimation in the output beams. The effects of these distortions became manifest when an attempt was made to bring the emerging digit-beams to a common focus with a minimum circle of confusion and combine them with the reference-beam to form the hologram exposing spot. In the signal path of the recorder, a lens (the hologram lens) is used to converge the emerging digit-beams from the page-composer and superpose them at a single-point on the central optical axis, where a small (square-section) aperture is placed. The latter is used as a field-stop to rigidly define the size of the recorded hologram. The focal length of the hologram lens was chosen such that, in the diffraction-limited situation, approximately 75% of the incident light on the field-stop aperture would be transmitted and the intensity distribution of the emerging digit-beams would be substantially uniform. Thus, an overall assessment of the wave-front distortion was obtained by measuring the maximum transmission factor of the field-stop aperture. The factor measured for the second version of the page-composer, immediately following the initial alignment, was approximately 60% without the PLZT modulator plate but this was reduced to 50% with the modulator plate installed. Apart from two digit-beams, which were low in intensity due to a registration error in fabricating the electrode gaps on the PLZT slice, the remainder of the beams emerging from the field-stop aperture varied in intensity by approximately ± 30%.

2.4.3 Modulation efficiency

The modulation efficiency was measured by forming a real-image of the field-stop on the photocathode of a photomultiplier tube using a projection lens system. A Wollaston prism was placed in a collimated part of the projection system to spatially separate the image into two components with orthogonal polarisation directions. The output of the photomultiplier was amplified and connected to an oscilloscope. The reference-beam was obscured leaving only the 50 digit-beams in the signal path, and their average modulation characteristics were observed for various switching rates and applied voltage. The electrical drive waveform was applied to all the modulator ports simultaneously; two of the ports were open-circuited due to breaks in the lead-in metallisation on the PLZT slice.

With an ideal page-composer, the light emerging from the field-stop aperture is deflected completely from one Wollaston image position to the other by switching between zero voltage and a fixed half-wave voltage, V_π, irrespective of the number of voltage transitions per second. A known limitation of PLZT, however, is its high dielectric loss (see Ref. 2) which causes considerable heating at the optical ports, where the electric field is strong, when the switching rate is high. The effect of the heating is to reduce the electro-optic effect and thus increase the value of V_π. Unfortunately, increasing the applied voltage to compensate, in turn produces further heating in the gap.

Fig. 8 shows some results obtained for the average modulation efficiency of the page-composer

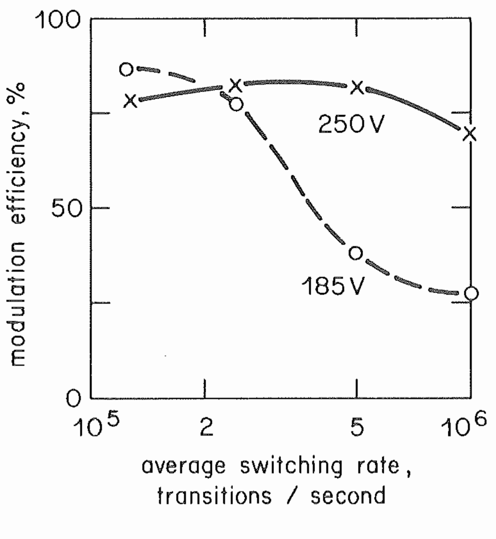


Fig. 8 - Modulation efficiency of the page-composer

for a range of switching rates (up to the maximum of 10^6 transitions per second). The modulation efficiency is defined as the fraction of the total light emerging from the field-stop aperture which can be switched from one Wollaston image position to the other. The dashed line in Fig. 8 is the result obtained when switching between 0 and 185 V and the full line for 0 to 250 V. These results suggest that the optimum applied voltage will depend on the statistics of the digital data applied to the page-composer.

Although dielectric heating limits the modulation efficiency, the rise and fall times of the switch transitions appeared to be unaffected and remained at about 100 ns.

The stability of the "off" state, i.e. with zero applied voltage, was also found to be unaffected by the dielectric heating; the maximum contrast ratio was, in fact, limited by adventitious perturbations of the polarisation characteristics introduced by other components (e.g. mirrors) in the system.

2.4.4 Bulk heating

The temperature of the PLZT modulator housing exterior stabilised at 50° C after a period of 90 minutes with all the ports switching between 0 and 250 V at a rate of 10^6 transitions per second. No attempt was made to treat the external surfaces of the metal housing in order to increase its emissivity.

2.4.5 Crosstalk and noise

The presence of crosstalk has been referred to earlier. With the present fabrication design of the PLZT modulator plate and the modified driver circuits, crosstalk is virtually eliminated and is well below the electrical noise level. A precise measurement is difficult to make but it is estimated that both crosstalk and noise are between 30 dB and 40 dB below the signal level which exists when a port is driven.

2.5 Further development

Many test recordings were made using the page-composer but with the ports switching at low rates[8]. These showed that the page-composer operated satisfactorily and on/off contrast ratios in the reconstructed digit-beams greater than 10 : 1 were achieved in some recordings. Further investigations were curtailed, unfortunately, after the page-composer was run continuously at the maximum rate (10^6 transitions per second). Many of the digit-beams dropped in intensity and their ports appeared to be permanently damaged. An examination of the modulator plate showed a build-up of micro-bubbles in a layer of silicone cement used to attach the cover glass to the PLZT slice. The bubbles were created by the heat generated in the electrode gap region. The photographs in Fig. 9 show the electrode gaps of two different ports on the modulator plate, one of which (Fig. 9(a)) was not switching due to a lead-in failure in the original fabrication; in Fig. 9(b) the bubble formation is clearly seen. Further developments of the page-composer would need to concentrate on the fabrication technology and, in particular, on finding better materials for covering the electrode

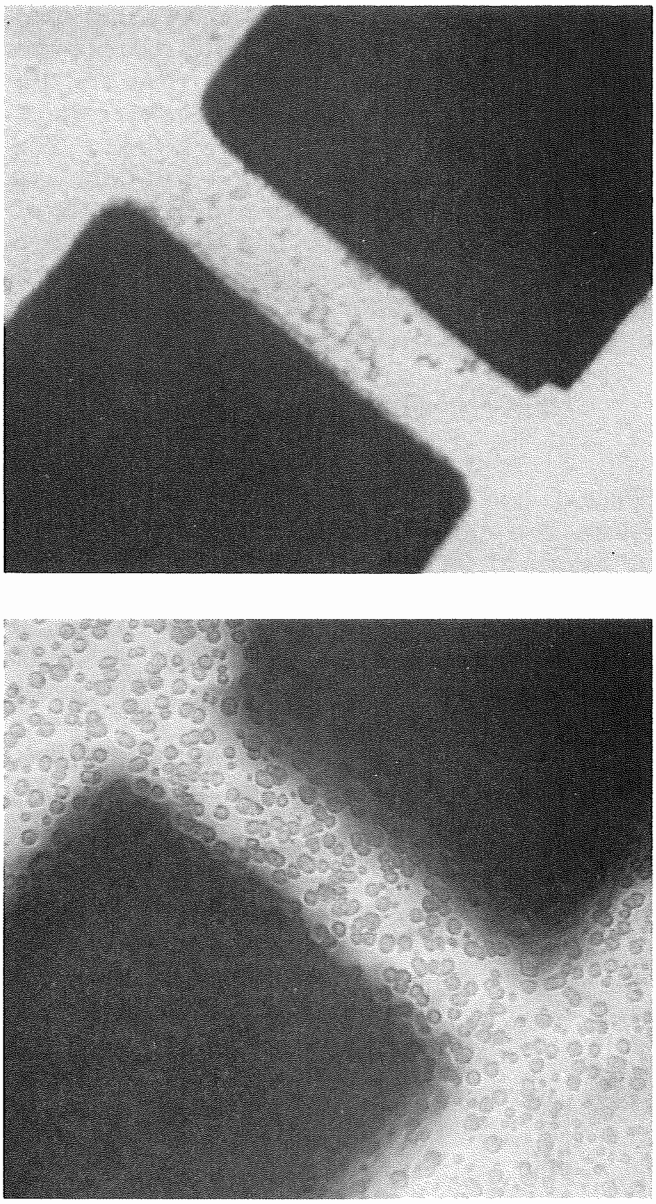


Fig. 9 - Photomicrographs showing bubble formation in the electrode gaps.

(a) Unswitched electrode gap.
(b) After switching at 10^6 transitions/sec.

gaps and dissipating the heat generated, while maintaining good optical transmission.

The modulation efficiency could be considerably improved by adopting a reflection mode of construction in which the light passes twice through the electrode gaps. This would drastically reduce the half-wave voltage required and, consequently, the local temperature of the PLZT in the region of the electrode gaps.

3. Digital light-deflector

Looking ahead, it seemed that an attractive feature of any future generation of video optical recorder would be that it contained no moving parts except for a relatively slow transport of the recording medium from reel-to-reel. Laser-beam deflection, if required at all, should be achieved by means other than the traditional mechanical methods, such as rotating mirrors or prisms. The solid-stage digital light-deflector arrangements proposed by Nelson[6], and later by Tabor[7], appeared to be the most elegant solution, especially as only a single axis of deflection with modest resolution (128 spots) was required. However, such a digital light-deflector, using electro-optic crystals and passive prisms, was expected to be a difficult and expensive transducer to engineer, and would be the primary constraint on the optical design of the recording system.

A digital light-deflector comprises a number *(n)* of binary deflection stages in tandem and generates at the recording plane a fixed array of 2^n hologram positions which can be individually addressed. Thus the resolution of the deflector (number of output locations) is doubled each time another stage is added. In a fully-populated (100 Mbit/s) recorder, seven stages would be required for recording a row of 128 holograms but, for tests with a partially-populated version, only four stages were constructed and assembled.

The principles and characteristics of this method of laser-beam deflection were outlined in a previous report[2]. A considerable amount of development work was required in order to fabricate a version of the deflector which would accommodate 50 parallel digit-beams (plus the central reference-beam), have a high optical transmission and operate efficiently at switching rates up to 10^6 transitions/sec.

No less formidable a task was to design and construct high-voltage (2 kV) switches in order to drive the electro-optic transducers in the deflector at these fast rates with transition times less than 200 ns.

3.1 General requirements

The general aims and performance objectives which were pursued in the development of a 4-stage deflector can be stated as follows:

(a) to record sequentially a row of sixteen juxtaposed holograms and achieve a constant quality of hologram along the row.

(b) to transfer the exposing radiation to the next location required in less than 100 ns and dwell for 500 ns while the film is exposed.

(c) to avoid an excessive build-up of crosstalk between holograms by achieving good optical and electrical switching efficiencies at each stage of the deflector.

(d) to achieve an optical transmission factor for blue light (λ = 441 nm) better than 70%.

(e) to minimise the drive power required for continuous operation.

Apart from some glass plates, the optical paths traversed by the digit and reference-beams are through crystalline materials which were obtained as optically-worked components from commercial suppliers. One aim was to test whether the tolerances specified for the optical quality of these components are sufficiently tight for this application, where many such components are assembled in tandem and a near-diffraction-limited performance is desired.

In the design of the deflector, a compromise was necessary between the conflicting electrical and optical requirements for its optimum performance. Moreover, there were known fundamental limitations in the electro-optic polarisation switches which influenced the way in which the switching voltages were applied to the first large-aperture stage (see Section 3.2 below). Another important consideration was to minimise the power dissipated by the transistors in the high-voltage switches.

3.2 Basic arrangement and construction

The deflection arrangement which was used for the experimental partially-populated recorder is

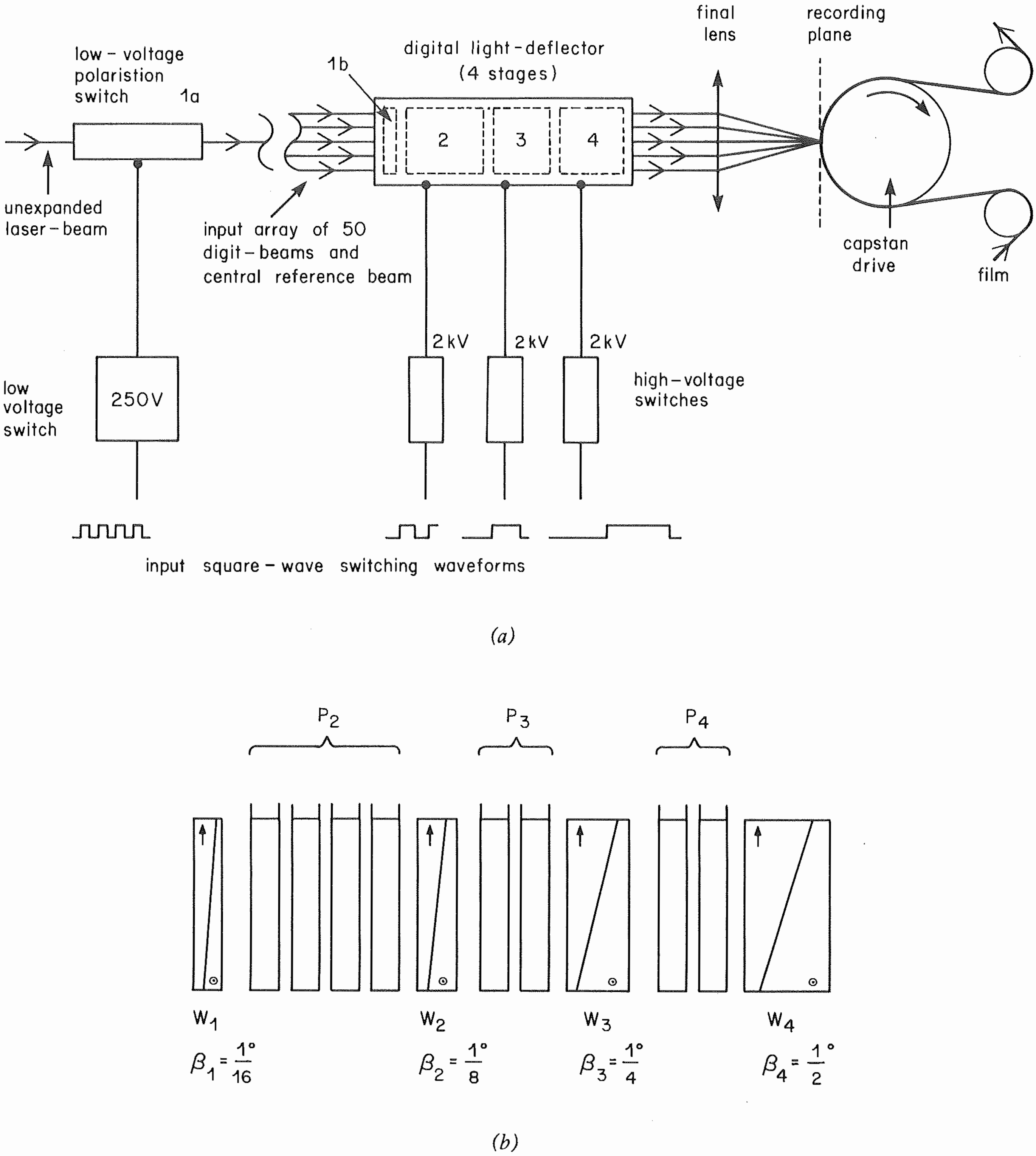


Fig. 10 - The digital light-deflector

(a) Arrangement in experimental partially-populated recorder.

(b) Vertical section showing crystal arrangement

P = polarisation switches, KD*P 20 mm x 20 mm aperture

W = Wollaston prisms (crystalline quartz) 25 mm x 25 mm aperture

β = deflection angle of Wollaston prisms shown schematically in Fig. 10(a). This shows that the 4-stage digital light-deflector is the last component in the optical recording chain except for the final lens. The deflector is a 4-stage, single-axis device with a deflection plane normal to the diagram. Each stage of the deflector consists of a Wollaston prism preceded by an electro-optic polarisation switch (the construction of these and the high-voltage drivers is discussed in detail in the following Sections). The crystalline components in the deflector have a sufficiently large aperture (20 mm x 20 mm) to accommodate the collimated array of digit-beams, generated and modulated by the preceding page-composer in the signal path.

Stage 1 in the deflector switches at the fastest rate (2 x 10^6 transitions/sec) and because of the limitations due to internal heating of large-aperture high-voltage (KD*P) polarisation switches, it was necessary to use a low-voltage type of switch instead, to achieve this switching rate. The low-voltage switch used (labelled 1(a) in Fig. 10(a)) was a small-aperture device (2 mm x 2 mm) which could not accommodate the digit-beam array. It was therefore separated from its Wollaston prism (1(b) in Fig. 10(a)) and placed at the beginning of the optical chain before the laser beam is split into separate reference-and signal-beams. The low-voltage switch, however, performs exactly the same function as the other polarisation switches in the deflector, i.e. to rotate the plane of polarisation of the incident light through 90° when a suitable voltage, V_π, is applied.

The four Wollaston prisms were fabricated from crystalline quartz, and produce angular separations between the orthongonal polarisation components of 1/16, 1/8, 1/4, 1/2 degrees, respectively. The arrangement of the prisms and crystal axes are shown in Fig. 10(b).

3.3 Fabrication of the polarisation switches

The polarisation switches developed for the digital light-deflector were based on the longitudinal type of Pockell's cell[9]. In this design, both the applied electric field and the light propagation are directed along the optical axis (*Z*-axis) of the electro-optic crystal.

A basic cell or switch unit was developed using single crystals (20 mm x 20 mm x 5 mm thick) of 0° *Z*-cut KD*P, with ladder-grid electrodes for generating the electric field. The form of construction of a basic cell is indicated in Fig. 11(a), which shows an exploded view of the components, The ladder-grid electrodes were formed on glass plates (1 mm thick) by etching an evaporated aluminium film through a photo-resist mask. These plates were cemented to the crystal faces to provide the clamping required to inhibit the unwanted piezo-electric resonances which can mar the switching performance. The crystal edges were surrounded by glass blocks, cemented in position to form a sealed unit. This is important because of the hygroscopic nature of the KD*P crystals, and in this form the units can be handled quite safely in a normal laboratory environment.

The collimated digit-beams traversing the deflector pass through slots (20 mm long x 1 mm wide) in the ladder-grid electrodes which on assembly are aligned with the deflection plane defined by the Wollaston prisms. The positions of the beams relative to the ladder-grid are shown in Fig. 11(b). It is clearly important that, because a number of these basic cells are used in tandem, the ladder-grid structures are capable of precise alignment. In preparing the electrodes, the glass substrates were selected for flatness and one edge chosen as a reference for alignment and registration in the subsequent photo-fabrication and cementing processes. A photograph of a complete cell is shown in Fig. 11(c).

At first, a thermoplastic cement was used to construct the cells but an epoxy-type resin cured by ultra-violet light was subsequently found to be easier and safer to use. Although possessing excellent optical and electrical insulation properties, the thermoplastic cement was difficult to apply because of the heating (120° C) required. The crystals are sensitive to thermal and mechanical shock and it was found that the heating process sometimes resulted in severe structural damage.

In blue light (λ = 441 nm), the measured half-wave voltage of the cells was approximately 4 kV. This is higher than was expected for the highly deuterated KD*P material in use, even allowing for the thin cement layers between the electrodes and the crystal surfaces. The degree of deuteration was suspected.

To reduce the switching voltage required to 2 kV, the 90° polarisation switches were made up from two basic cells in tandem as shown in Fig. 12. The X-Y crystallographic axes of the crystals were crossed, as indicated in the Figure, and the applied field was reversed in one cell relative to that in the other. This results in the addition of the induced birefringences, so that the effective half-wave voltage, V_π, becomes 2 kV for the two cells in tandem. The polarisation switches have no d.c. response, because of the high insulation of the cement layers, so that for some switching arrange-

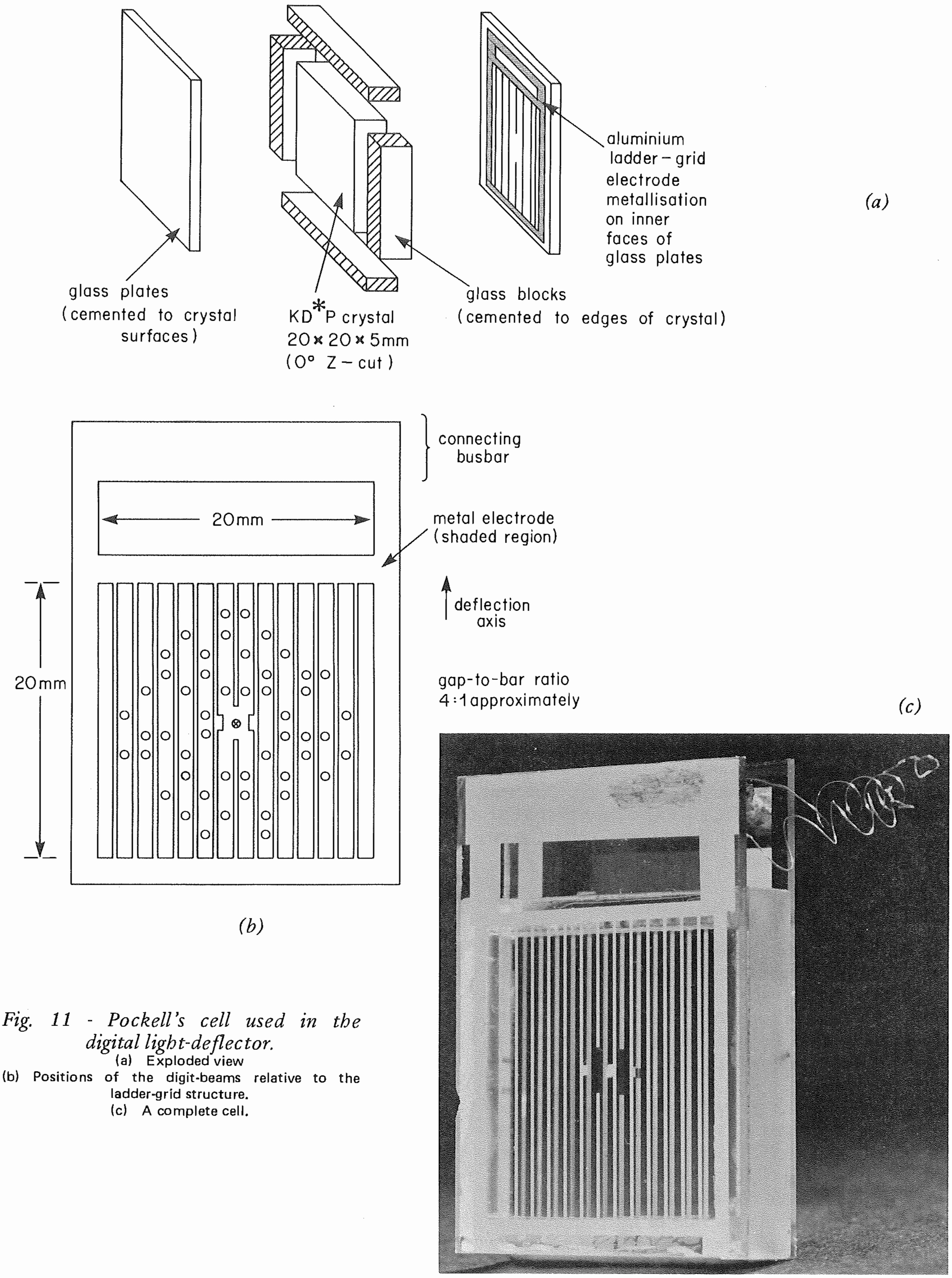

aluminium ladder – grid electrode metallisation on inner faces of glass plates
(a)
glass plates (cemented to crystal surfaces)
KD*P crystal 20 × 20 × 5mm (0° Z – cut)
glass blocks (cemented to edges of crystal)
connecting busbar
20mm
metal electrode (shaded region)
deflection axis
20mm
gap-to-bar ratio 4:1 approximately
(c)
(b)

Fig. 11 - Pockell's cell used in the digital light-deflector.
(a) Exploded view
(b) Positions of the digit-beams relative to the ladder-grid structure.
(c) A complete cell.

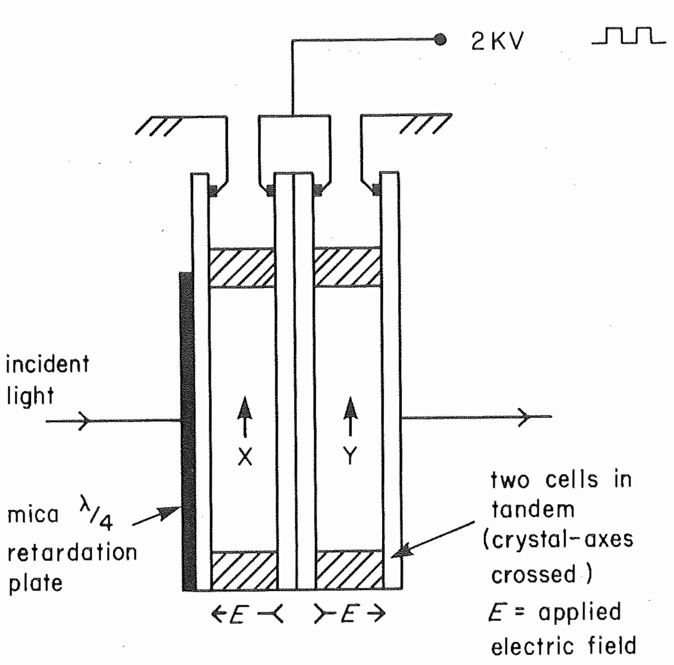

2 KV
incident light
X
Y
mica λ/4 retardation plate
two cells in tandem (crystal-axes crossed)
E = applied electric field
←E→ ←E→

Fig. 12 - Polarisation switch using two Pockell's cells

ments (e.g. when applying a continuous square-wave periodic waveform) it is necessary to provide an optical bias to compensate for the loss of the d.c. component (see Reference 9). Cleaved mica retardation plates can be used for this purpose, although the plates are slightly absorptive for blue light (≃ 8% for a λ/4 plate).

For the fastest, large-aperture stage of the deflector (P_2 in Fig. 10(b)) two pairs of cells were used to make up the polarisation switch; the switching arrangements for this stage are described in Section 3.5.

3.4 The high-voltage switches

The circuit and output waveform of the electronic switches used to drive the deflector stages have been described in a previous Report^2. The drivers maintain their performance over long periods, with transition times of about 200 ns. At the outset of the work to develop these switches, it was stated that transition times of 100 ns would be preferred. Unfortunately, no suitable commercially-available transitor is known which achieves this switching performance at the high voltages required. The new generation of V-groove f.e.t.'s is, however, an encouraging sign that a suitable device may be available shortly.

The pair of electro-optic cells, forming a large-aperture polarisation switch in the deflector, presented a capacitive load of about 30 pF to the electronic driver. For a given load capacitance and half-wave voltage, the average power required to drive the switch is directly proportional to the switching rate. Moreover, the energy drawn from the power supply has to be dissipated in the drive circuits, mainly by the chain of output transistors. In the experimental deflector, the fastest large-aperture stage, operating at 10^6 transitions/sec and with a half-wave voltage of 2 kV, required 240 W of power. This is greater than the total power requirement for all the subsequent deflector stages, irres-

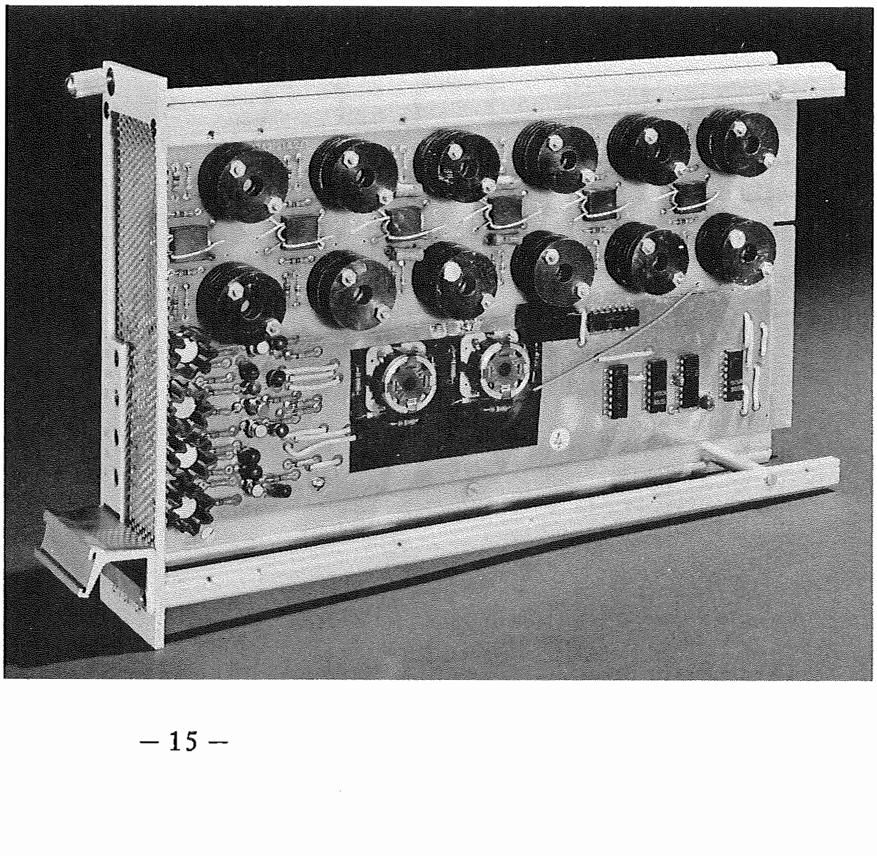


Fig. 13
A 2 kV switch unit
(side-panel removed)

pective of number, because of the binary relationship between their drive frequencies.

A prototype switching unit for one of the fast stages is shown in Fig. 13. Extra heat sinks have been fitted to the power transistors in an attempt to allow forced-air cooling to be used instead of pumped-oil cooling. The high operating half-wave voltage of the KD*P crystals (2 kV instead of an anticipated 1.7 kV) has, however, increased the power to be dissipated within the driver by 40%. So far, the fastest stages have been operating intermittently at 1.7 kV using forced-air cooling, and measured heatsink temperatures indicate that further heat dissipation is not practicable. Methods of overcoming this limitation will require further investigation.

A 600 W, 2 kV switch-mode power supply was constructed for the complete deflector.

3.5 Switching arrangements and characteristics

The *n* stages of the deflector are individually addressed by means of periodic synchronous waveforms derived from a hologram address number which is locked to television line-frequency. The control waveforms for a four-stage deflector are given in Fig. 14, where it will be noted that the two fastest stages require different switching waveforms from the others.

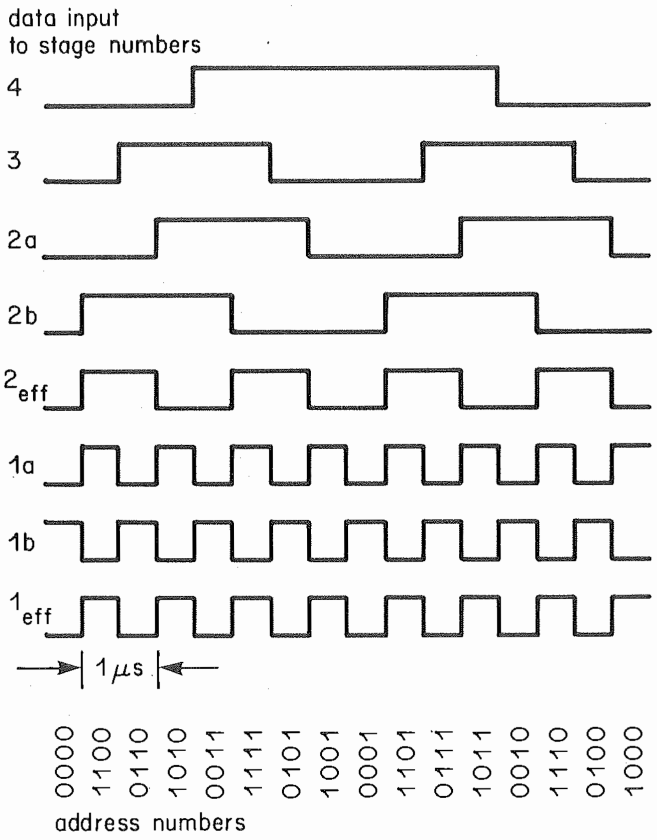


Fig. 14 - Switching waveforms for a four-stage deflector.

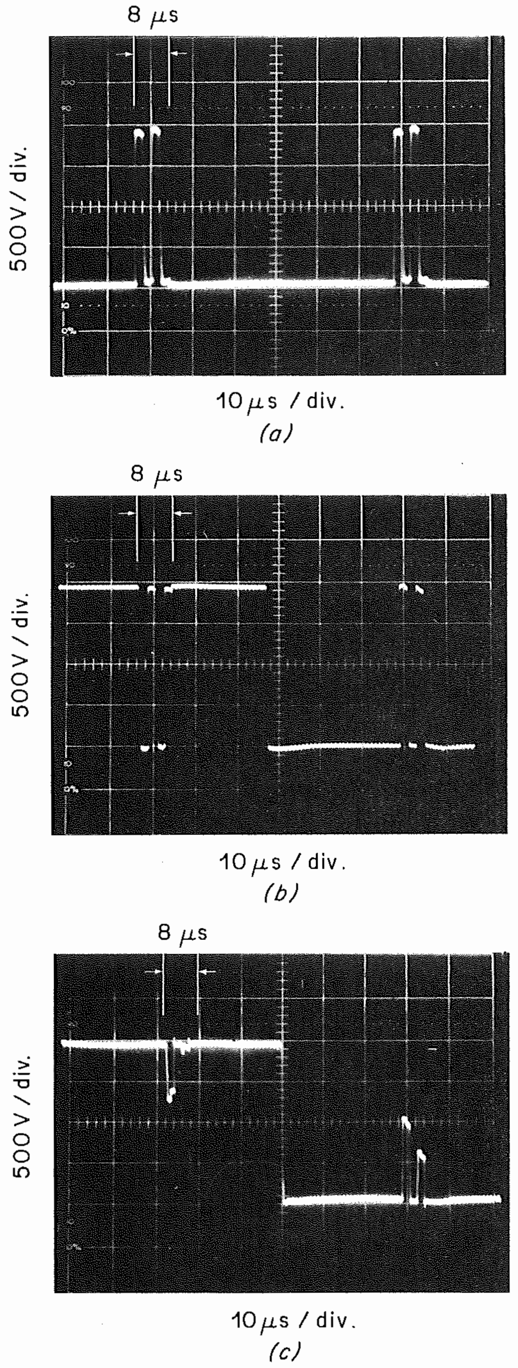


Fig. 15 - High voltage switching pulses at stage 3, for two drive arrangements.

(a) Normal drive arrangement.
(b) A push-pull arrangement.
(c) Breakthrough pulses on the neutral line with a push-pull arrangement.

The large-aperture Pockell's cells are limited by internal heating effects to a maximum frequency of 250 kHz for continuous operation. The second fastest stage (No. 2), which is required to operate at 500 kHz, therefore comprises two pairs of cells in tandem. Each pair is driven at 250 kHz, but the two drive waveforms are 90° out of phase with each other. These are referred to as 2a and 2b in Fig. 14. The effective switching waveform of the combination (2_{eff} in Fig. 14) allows this stage to be effectively operated at 500 kHz.

The fastest stage (No. 1), which uses a low-voltage (350 V) small-aperture modulator at the beginning of the optical path, is driven by two anti-phased drive waveforms at 1 MHz, shown as 1a and 1b in Fig. 14; the combined switching effect is shown in 1_{eff}. It was necessary to provide a time delay in the drive to the low-voltage first stage to compensate for a 650 ns relative delay inherent in the 2 kV driver stages.

Various optical and electrical measurements on a four-stage deflector were carried out and these are described in the next Section. For some experiments, the drive pulses were present for only one-eighth of a line period. A typical high-voltage drive waveform for stage 3 is shown in Fig. 15(a), where the high-voltage switching pulses are applied to the central electrodes of a pair of Pockell's cells (see Fig. 12).

An alternative drive arrangement which would eliminate the need for optical retardation plates was investigated. The drive data was inverted on alternate television lines. Similarly, the drive to the neutral (outer) terminals of the cells was inverted. This has the effect of switching with ±2 kV on alternate lines and provides a balanced

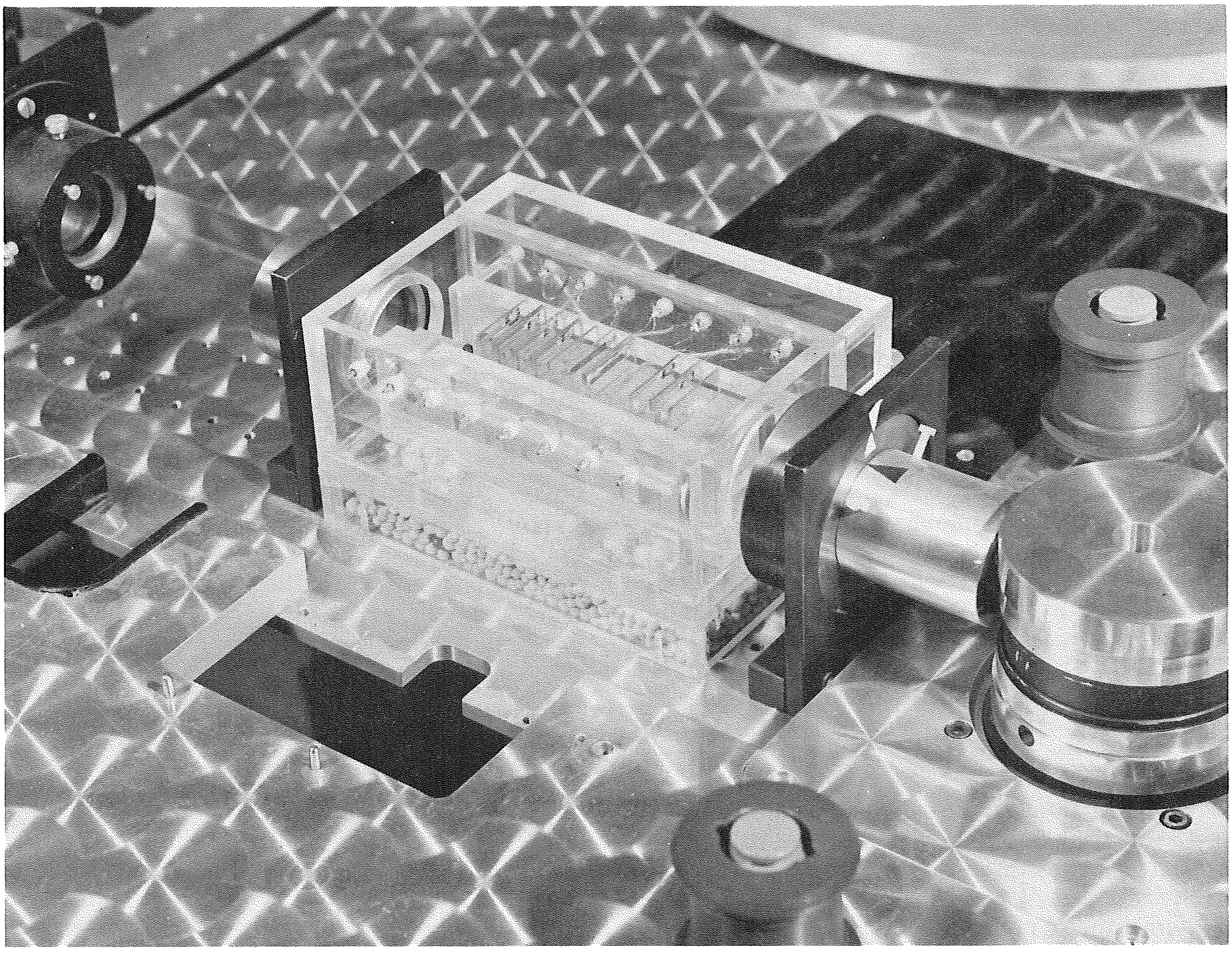


Fig. 16 - Digital light-deflector in the recorder

push-pull drive. A typical high-voltage drive waveform for this situation is shown in Fig. 15(b). Unfortunately, the effective neutral drive signal suffered from a breakthrough of the data from the main drive signal because the output impedance of a driver stage is comparable with that of the cell being driven. The effect is, however, not purely a capacitative potential-dividing action because, as can be seen from Fig. 15(c), the data breakthrough pulses on the neutral terminals are unequal within a line period and from one line to another. Further investigation is needed here to determine the reasons for this effect.

3.6 Some results for a four-stage deflector

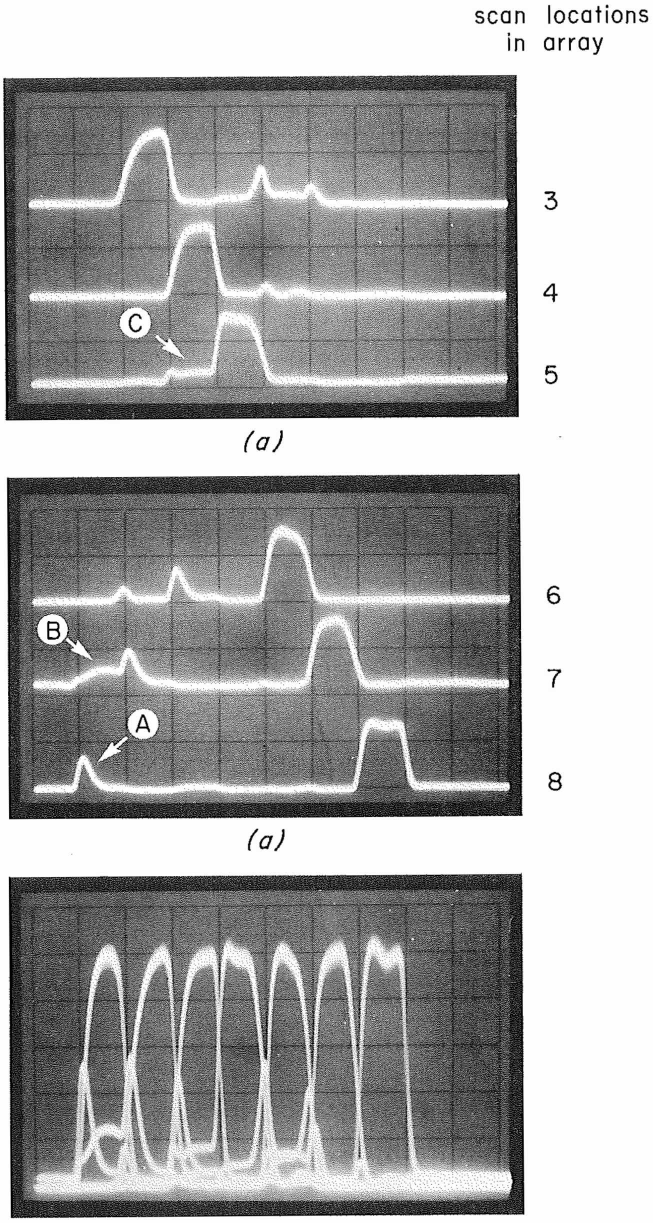
Fig. 16 shows a four-stage version of a single-axis digital light-deflector located in the experimental recorder.

The deflector contains eight KD*P electro-optic cells, each with a pair of ladder-grid electrodes as described earlier, and a set of four Wollaston prisms. These components were aligned and sandwiched together, using a transparent index-matching oil between the contacting surfaces. The complete assembly is 90 mm long, with a maximum optical aperture of 20 x 20 mm, and is housed inside a Perspex box containing a dessicant. The field electrodes are wired to lead-through terminals on the side of the box. A low-capacity frame of insulated wires is used to couple the deflector to the high-voltage switch units. The measured optical transmission loss was 26% for the central reference beam but rather more, 40%, for the digit-beams. This difference is due to the slightly greater degree of obstruction of the digit-beams by the ladder-grid metallisation on the electrodes.

A significant amount of unwanted stray light was observed in the recording plane, caused by multiple specular reflections from the ladder grids within the deflector. This effect is exacerbated by the high specular reflection coefficient of the aluminium electrodes used for the ladder grids; for blue light, as used in the recorder, copper or bronze would have been a more suitable metal for constructing the electrodes.

It was anticipated that there would be some spatial distortion of the phase of the collimated light transmitted through the deflector because of stress-induced and natural inhomogeneities in the refractive index of the various crystals. Indeed, this effect was clearly seen by examining the quality of the hologram-forming images in the recording plane both with and without the deflector; the image definition appeared to be slightly inferior with the deflector *in situ* and there was also a small change in the optimum focus position.

Another passive effect, which occured with no voltages applied to the electro-optic switches,



(a)

(a)

(b)

Fig. 17 - Scanning performance of the experimental four-stage deflector.
(a) The average light intensity versus time at each of six consecutive locations in the scan array.
(b) Superposition of the information shown in (a)

was the appearance of faint ghost images at some of the hologram locations other than the first (rest position). These spurious images were caused by small misorientations of the KD*P crystals such that their optic-axes were not mutually parallel, but slightly skew. Careful angular adjustment of the whole assembly with respect to the incident collimated beams reduced this passive ghosting to levels which were not serious.

The electro-optic switches were driven so as to produce a regular scan of the 16 output locations, using control waveforms of the type previously shown in Fig. 14. A scan of all the 16 locations takes 8 μs, although the first location is also illuminated for the remainder of the 64 μs television line period before the start of the next scan.

The oscilloscope traces shown in Fig. 17 illustrate the performance achieved with the experimental deflector. By means of a photomultiplier detector, followed by a wide-band amplifier, the average light intensity as a function of time could be examined at each hologram location in turn. The set of traces in Fig. 17(a) shows the results obtained for a set of six consecutive locations (Nos. 3 to 8 inclusive) in the scan array. The general scanning action may be seen by the progression of the main pulse of light from left to right in the Figure, where the horizontal time scale is 500 ns per division.

The pulse of light at each location lasts for about 500 ns, as expected, and in an ideal deflector it would be the only pulse occurring until the next cycle of scan. The narrower secondary pulses appearing in the traces are principally due to the difference in the switching transition times between that of the first stage and the other three. The secondary pulse marked A in Fig. 17(a), for example, has a sharp leading edge corresponding to the fast (100 ns) 'on' transition of the first stage and a less steep trailing edge due to the simultaneous, but slower (200 ns), transition of the second stage. These spurious pulses would give rise, in a recording, to hologram crosstalk. An estimate of the amount of crosstalk is obtained by comparing the area of the main to the subsidiary (transition-derived) pulses; for the traces shown the crosstalk levels are about 10%.

The traces in Fig. 17(a) also reveal two other imperfections of the experimental deflector. The 'bump' marked B in the trace at the 7th location is due to an unwanted piezo-electric resonance of the third stage KD*P crystal. In a fully-populated version, where each stage is driven continuously, this resonance effect at the third stage would be expected to disappear. The pedestal marked C, just preceding the main pulse at the 5th location, is due to insufficient applied voltage at one of the stages, so that the half-wave voltage was not reached and the optical switching was therefore incomplete.

The traces in Fig. 17(a) were expanded and superposed in order to produce, by multiple exposures, the result shown in Fig. 17(b). Here, the switching efficiency and degree of synchronisation can be more easily compared.

From the results obtained, it is clear that the deflector performance, for this particular application, is principally limited by the relatively slow transition times (200–250 ns) of the large aperture electro-optic switches. However, the existing crosstalk levels are not believed to be a serious problem, providing that low-order crystal resonances are suppressed.

3.7 Extension to seven or eight stages

The number of deflector output locations can be increased in binary jumps simply by adding more stages; for example, a fully-populated recorder would require three additional stages to obtain 128 output locations.

Apart from a possible further deterioration in the definition of the hologram spots, the main problem is expected to arise from piezo-electric resonances. The fundamental frequencies of the square waves required for driving the KD*P crystals of the 5th to the 7th stages lie in the range 16 to 64 kHz. This range, unfortunately, straddles the frequencies of the lowest order resonance modes of the crystals[2]. Great care in design will be needed to ensure a spectral interleaving of the drive harmonics with those of the crystals at each stage. Moreover, the crystals will need to be mechanically clamped as rigidly as possible.

The drive power required for the additional stages is very small and the high voltage switches could run without any special transistor cooling arrangements.

In order to improve crosstalk levels, it might be necessary to add an eighth stage in which the Wollaston prism is replaced by a polariser. This stage would be switched to allow only the wanted beams to be transmitted and block the principal spurious components which are always polarised orthogonally.

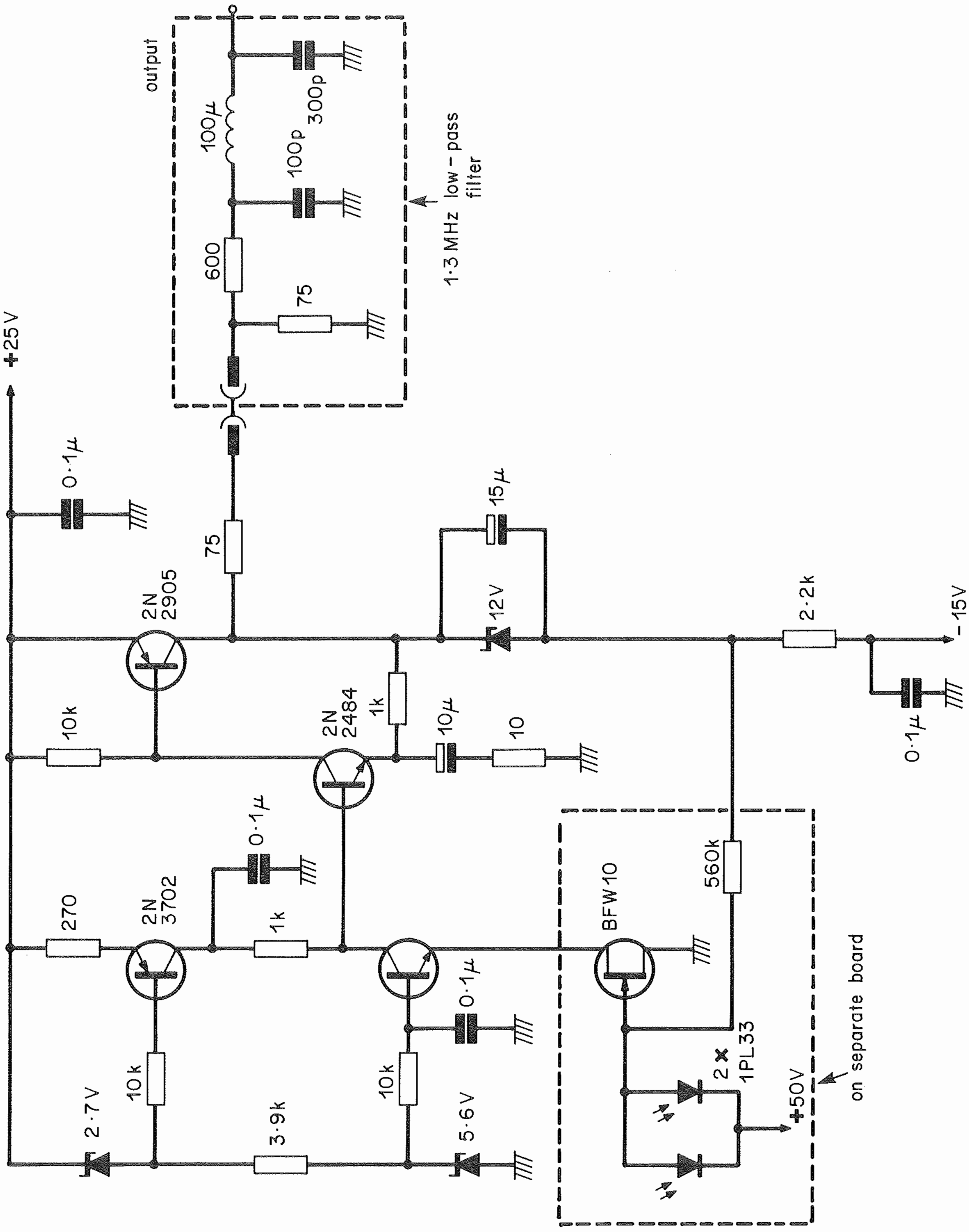


Fig. 18 - Photodiode amplifier circuit and filter

4. Photodetector array

Although two-dimensional integrated photodetector arrays were available, these did not meet the detection requirements, especially at the low light-levels associated with hologram reconstructions using low-power lasers. A study showed that the required bandwidths and signal-to-noise ratios could be obtained using inexpensive silicon photodiodes and field-effect transistor (f.e.t.) amplifiers.

4.1 Basic requirements

To detect the 50 pairs of digit-beams in the reconstructed hologram image, one hundred photodetectors are required to operate with incident light levels up to ½ μW and with bandwidths up to 2 MHz. Sufficient amplification is necessary to provide electrical signals suitable for subsequent decoding with a signal-to-noise ratio greater than 26 dB* per channel (two photodiodes per channel).

The choice of detector was restricted by the requirement for it to be inexpensive, small and low-noise. Photomultipliers were considered because of their good overall noise performance but they require stabilised e.h.t. supplies and they are large, expensive and fragile. Silicon avalanche photodiodes were also ruled out because of cost. Silicon photodiodes, which are both small and inexpensive, have no intrinsic gain and an external low-noise amplifier is therefore required. It was shown, however, that with a suitable amplifier this latter choice was potentially capable of offering a very good noise performance, comparable with a photomultiplier at these light levels.

Of several silicon photodiodes which were examined, the one selected was type IPL 33 manufactured by Integrated Photomatrix. This detector has an active area of 0.5 mm^2 (square format with 0.7 mm side) and a juntion capacitance of typically 12 pF. It has a sensitivity of about 0.4 A/W for red light, as used in the experimental replay apparatus, and it has an adequate bandwidth.

The small compact size of the hologram reconstruction prohibits 100 such photodiodes being formed into an array and used directly in the reconstruction plane. This problem was overcome by using 50 pairs of monofilament light-guides as a probe to intercept the hologram image and transmit the light from the digit-beams to the photodiodes.

4.2 Amplifier circuits

Theoretical considerations show that at high incident-light levels the shot-noise associated with the photodiode current is the limiting factor when assessing the overall signal-to-noise ratio of a photodiode-amplifier combination. At lower light levels, however, the choice of amplifying device is more important.

An f.e.t. generally offers the best choice of low-noise front-end for an amplifier, but an integrated f.e.t. operational amplifier was considered initially and its overall signal-to-noise ratio was found to be unacceptable for this application.

After several attempts, an amplifier circuit using discrete transistors was designed as shown in Fig. 18. The first amplifying stage is a BFW10 f.e.t. which has a gate capacitance of 3 pF and a g_m = 4mS. The amplifier is d.c. coupled throughout, although the exact d.c. level at the

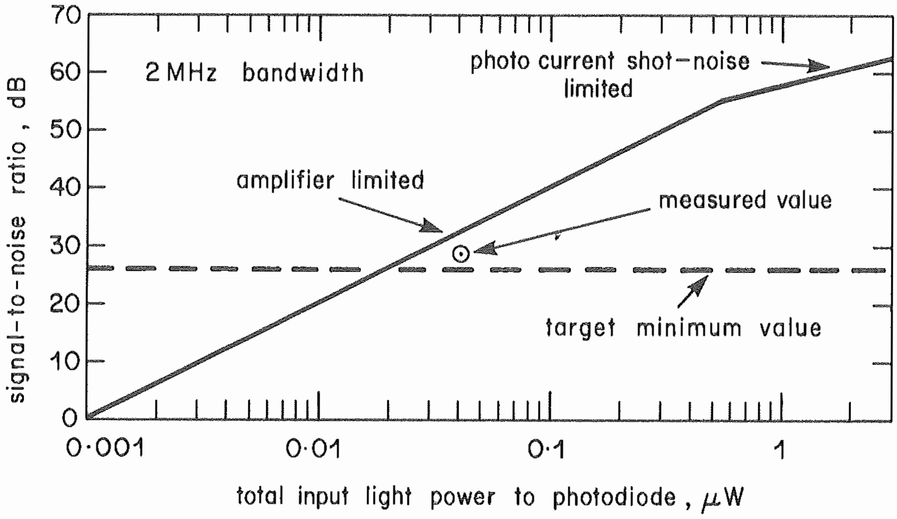


Fig. 19 - Signal-to-noise ratio of photodiode/amplifier combination, IPL33 photodiode, BFW10 f.e.t.

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* This figure, 26 dB, refers to the random noise in the detector which is the shot noise associated with the photodetector plus the amplifier noise.

output is not the same from one circuit to another (this could be corrected in a subsequent clamp stage). A 560 kΩ feedback resistor was found to give an optimum overall performance: this makes the overall sensitivity of the photodiode-amplifier equivalent to 224 mV/μW. The amplifier is simple, small and relatively inexpensive. The maximum theoretical noise performance is shown by the full line in Fig. 19.

4.3 Mechanical arrangement

The 50 amplifiers were arranged on 5 printed-circuit boards each containing 10 amplifiers: one of the boards is shown in Fig. 20. The photodiodes and feed-back resistors were mounted on separate sub-boards with a plug and socket connector for convenience.

The light-guides were connected to the photodiodes by a double epoxy-resin support as shown in Fig. 21. This method provides the necessary mechanical support, and the optical coupling efficiency is satisfactory. The ends of the light-guides were lapped and polished prior to assembly and laterally adjusted on test, before the bonding resin set, to give the optimum coupling efficiency. The fibres are nominally 0.75 mm in diameter, 0.6 m long and the measured overall optical transmission was about 70% including end-effects.

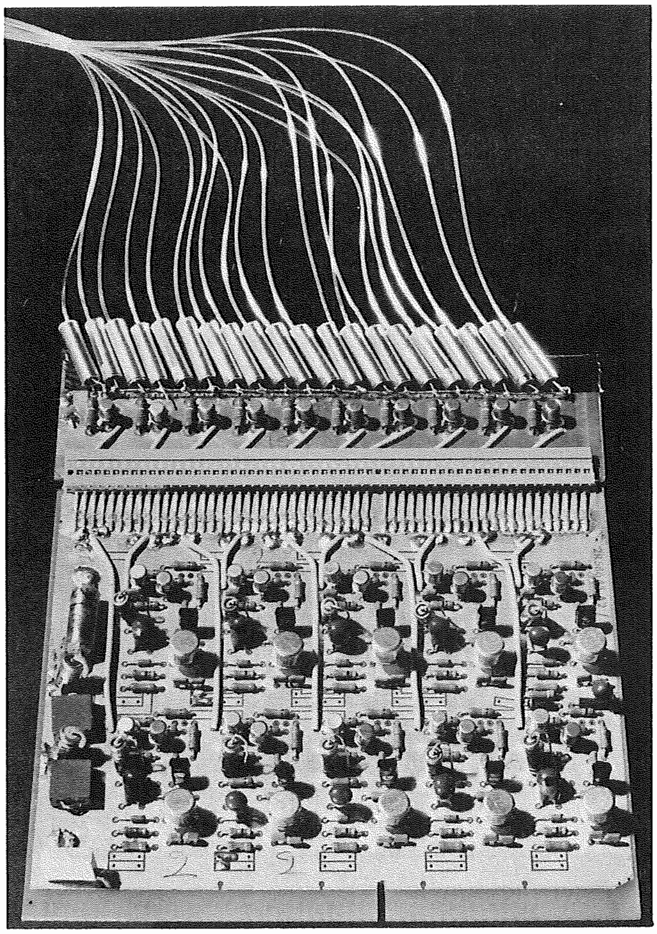

Fig. 20 - A photodiode/amplifier board.

The complete photodetector assembly is shown in Fig. 22.

4.4 Performance

A full description of the recordings made so far in this project and the overall performance of the recording and replay mechanism are given in a further Report[8].

A photodetector-amplifier was used, with a light-guide connected to one of the photodiodes, for detecting a digit-beam in the reconstruction of a scanned row of recorded holograms. Typically, for a digit-beam near to the centre of a page of data an average peak-to-trough output signal of 7.9 mV was measured when scanning a group of alternately modulated holograms. The corresponding noise in a 1.3 MHz bandwidth was 0.28 mV r.m.s. which is very close to the 0.23 mV value calculated from the f.e.t. data. The resulting signal-to-noise ratio for this digit-beam was 29 dB and the incident light power on the photodiode can be deduced as 0.042

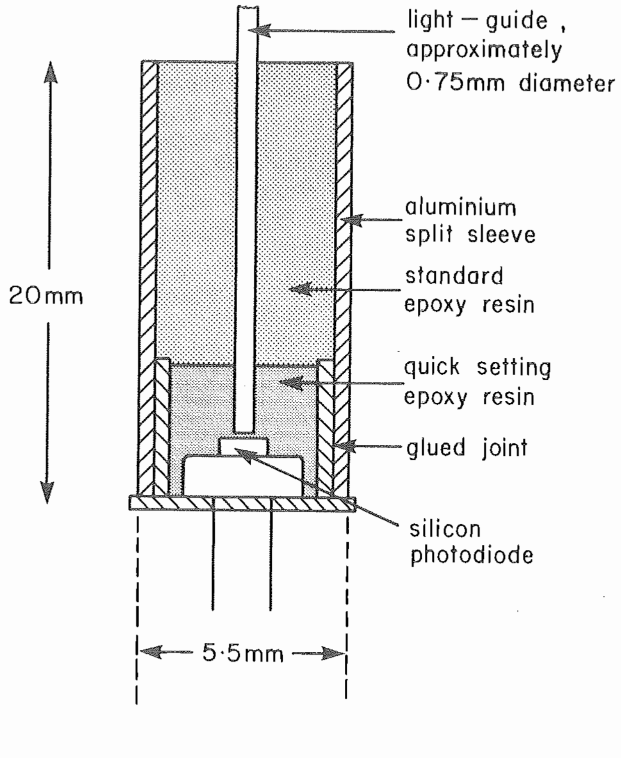

Fig. 21 - Cross-section of a light-guide/photodiode joint

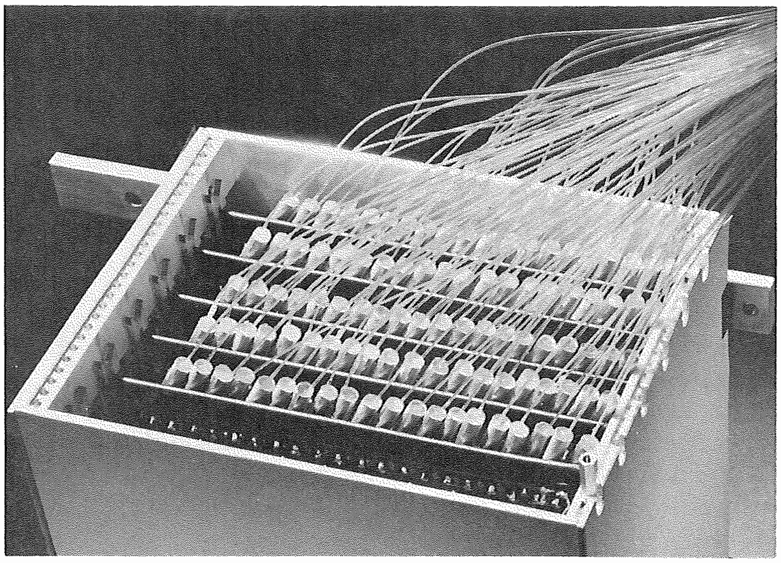

Fig. 22 - The photo-detector array (in box).

μW. (An allowance of 1.5 dB has been made for the insertion loss of the low-pass filter at the scanning rate used).

Allowing for a further 3 dB loss of signal in the light-guide and its end-effects, the target signal-to-noise ratio of 26 dB can be achieved with a minimum incident light power of 0.04 μW from the weakest digit-beam pair.

4.5 Further development

The mechanical arrangement of the input end of the light guides is as yet incomplete. The light-guides require a protecting sleeve and a pre-drilled metal plate to locate the inputs of the guides at the correct array positions in the page-composer configuration.

5. Conclusions

A hologram page-composer based on PLZT material for the modulator appears to be a feasible and low-cost method for up to 50 bits per page at least. Continued development would be desirable, however, to mitigate further the effects on the modulation performance and on the quality of the optical channels due to the localised dielectric heating at the highest switching rates (10^6 transitions/second). A successful method of fabricating a planar structure of electrodes, capable of providing intense electric fields at specific locations on the PLZT surface has been developed. A suitable optical cement for protecting the electrode structure and for removing the heat generated at the switching ports is still required. In the final arrangement adopted, interchannel crosstalk was found to be insignificant. The largest constructional problem was the matching and alignment of the input and output lenslet arrays. Special alignment and assembly methods were devised which proved to be reasonably successful, although somewhat tedious. It is essential that the lenslets used for the arrays are of good optical quality, and are precisely centred, if the generated digit-beams are to be sufficiently aberration-free to form a near-diffraction limited image at the focus of the hologram lens. Beam wave-front distortions lead to a poor optical efficiency and large variations in the intensities between the digit-beams at the final recording plane. Although dielectric heating limits the digit-beam modulation efficiency at high data rates, the stability of the "off" state, i.e. with no volts applied, is unaffected. This is true, also, for the rise and fall times of the transitions which remained at approximately 100 ns.

The digital light-deflector, although elegant in concept and ideally suited in principle to this application, gave rise to several complications in its construction. The principal difficulty centred around first large-aperture stage of the device, where the polarisation switch in a fully-populated recorder is required to operate at 10^6 transitions per second and yet have an aperture of 20 mm x 20 mm. The drive-power required for this stage only was greater than 200 W and, at a voltage of 2 kV, this imposed a strain on the design of the switch circuits. On all the stages, the minimum time taken to deflect the exposing spot from one hologram location to any other was approximately 200 ns, whereas a time of 100 ns would have been preferred; future developments in high-voltage transitors could remove this limitation. The KD*P crystals used are expensive and future designs of deflector should aim at reducing the material volume to a minimum. They are also prone to damage, but when formed into basic cells by cementing between glass plates the units are quite stable, consistent in operation and can be handled safely. Piezo-electric resonances, although heavily damped, can still cause problems when switching at low rates (from 16 to 64 kHz). The optical transmission of the deflector was reduced principally by the absorption of the mica retardation plates used for optical biasing in each stage. However, overall transmission factors greater than 60% are possible when the components are immersed in an index-matching liquid to avoid surface reflection losses. A significant amount of unwanted stray light was generated in the recording plane which is believed to be due to the high reflectance of the aluminium ladder-grid electrodes. Future designs should aim to use electrode materials with a low reflectance for blue light, e.g. copper or bronze.

The development of a suitable photodetector array, using discrete silicon photodiodes coupled to the reconstructed hologram image via a bundle of monofilament light-guides, was reasonably straightforward. By designing a low-noise amplifier circuit using input f.e.t's, and by optimum low-pass filtering, output signal-to-noise ratios greater than 26 dB were obtained in each channel for input light-levels of 0.04 μW. A method of attaching a monofilament light-guide to the silicon surface of a photodiode was developed which is both optically efficient and mechanically strong.

Overall, the development of the page-composer, the light-deflector, and the photodetector array, gave encouraging results regarding the feasibility of transducers for a 100 Mbit/s holographic recorder. The main unresolved problems are overheating in the page-composer, and inadequate performance of the switching circuits at the highest data rates in the light-deflector. Further work on these problems is in abeyance pending investigation of a more serious problem associated with the recording medium, reported in Reference 8.

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